

Catalytic Combustor for Fuel-Flexible Turbine
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ABSTRACT

Under the sponsorship of the U. S. Department of Energy's National Energy Technology Laboratory, Siemens Westinghouse is conducting a three-year program to develop an ultra low NO_x, fuel flexible catalytic combustor for gas turbine application in IGCC. The program is defined in three phases: Phase 1- Implementation Plan, Phase 2- Validation Testing and Phase 3 – Field Testing. The Phase 1 program has been completed. Phase II as initiated in October 2004.

In IGCC power plants, the gas turbine must be capable of operating on syngas as a primary fuel and an available back-up fuel such as natural gas. In this program the Rich Catalytic Lean (RCLTM) technology is being developed as an ultra low NO_x combustor. In this concept, ultra low NO_x is achieved by stabilizing a lean premix combustion process by using a catalytic reactor to react part of the fuel, increasing the fuel/air mixture temperature.

In Phase 1, the feasibility of the catalytic concept for syngas application has been evaluated and the key technology issues identified. In Phase II the catalytic concept will be demonstrated through subscale testing.

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EXECUTIVE SUMMARY

The Rich Catalytic Lean (RCLTM) technology, Figure 1, is being developed as an ultra low NO_x gas turbine combustor for Integrated Gasification Combined Cycle (IGCC). In this concept, ultra low NO_x is achieved by stabilizing a lean premix combustion process by using a catalytic reactor that produces a nominal gas temperature increase in the fuel/air mixture (by converting part of the fuel).

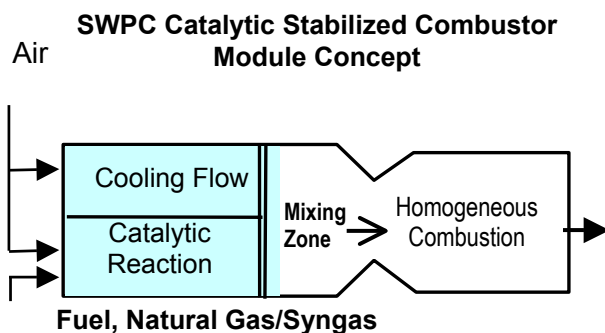


Figure 1 – SWPC Catalytic Stabilized Combustor

A key challenge in developing a fuel flexible catalytic combustor is the ability to provide one base design that will accommodate the different process flow conditions that are indicative of different IGCC plant designs. Cold Vs hot gas cleaning, degree that the gas turbine is integrated with the IGCC plant and how the plant might be optimized for efficiency Vs power output all impact the process flows that must be managed within the combustor. In Phase 1, the feasibility of the concept for syngas applications was evaluated, benchmarked and a validation test program (Phase 2) is defined. Specifically,

Catalytic module and combustor design concepts are defined for fuel flexible operation that minimize changes to the current catalytic reactor design, thus retaining the product of prior engineering and development. The proposed module design options are summarized in Table 1. In Phase 2 these design options will be developed, tested and evaluated.

Table 1 – Summary of Catalytic Combustor Design Options for IGCC

Concept Approach	Syngas Operation	Natural Gas Operation
No change to the current catalytic module design.	Options include staging or bypassing syngas and nitrogen to increase fuel conversion on the reactant side.	No impact
No change to the current catalytic module design. Utilize an eductor to control air split.	Syngas air split can be optimized but will require higher syngas pressure to drive the eductor.	No impact
Modify current catalytic module for syngas.	Can be optimized for syngas conversion.	Requires device to control air split during natural gas operation.

During Phase II these concepts will be developed and tested. The catalytic combustor and module product definition will be further developed for the IGCC W501FD engine application. The focus will be on improvements required for syngas and the higher firing temperature of the W501FD engine. Highlights of this phase of the project were testing of SWPC catalytic coatings on natural gas and syngas, redesign of the baseline catalytic module with dual fuel capabilities for natural gas and syngas and redesign and testing of the catalytic basket for the STG-5000F configuration.

TASK II.2 – SYNGAS CATALYSTS:

Single Tube Facility

The single tube facility was commissioned at Casselberry Labs. Figure 2 shows a picture of the single tube facility. In this facility a single coated tube can be tested at full 501FD engine conditions. The rig is designed to simulate the pressure, temperature and velocity of the flow streams at the inner and outer tube surface. The cooling air inside the tubes and the air to the rich reaction section outside the tube is independently controlled so variations in air split can be investigated. Natural gas is available to the rig and syngas is provided by bottles.

Highlights of the coating development work include:

- The light-off and re-light-off capabilities of new catalytic elements with Pd precious metal catalyst dispersed in ceramic based matrix were demonstrated in the single tube rig operated in natural gas environment. Tables 2 and 3 show the compositions of the natural gas and syngas tested. A comparison of the lightoff data for the SWPC Pd coating light off with the PCI coating is given in Table 4.
- Four different types of ceramic coating compositions were evaluated for the potential application as the washcoat for manufacture of catalytic elements. The catalytic elements were manufactured by applying different ceramic matrices with Pd catalyst on Haynes 230 substrates.
- The thermal and mechanical stability properties of catalytic elements, such as the adhesion of ceramic matrices to the nickel-base substrate and growth of Cr_2O_3 TGO layer (thermal grown Cr_2O_3 oxide) on the substrate-washcoat interface were evaluated by thermo-cyclic furnace test. This screening test was conducted at the accelerating conditions and helped to evaluate the coating performance at the extreme temperature and heating/cooling regime. Two out of four washcoat-substrate systems demonstrated the promising mechanical and thermal stability properties.
- Furnace thermo-cycling test is considered to be continued at three different temperatures (including the average operating temperature of coatings in the catalytic combustor) and the life prediction method for catalytic coatings performance should be established in future.
- Pd-catalyst agglomeration and crystallite formation in four ceramic matrices were evaluated over long-time by thermo-cycling test. Agglomeration of Pd particles was dependent on the composition of ceramic washcoat systems. At certain washcoat systems, the growth of Pd crystallites continued only for certain period of time and, after that, the size of Pd crystallites did not change. However, in other washcoat systems, agglomeration of Pd-particles continued during the full period of heat-treatment.
- The study of coating performance characteristics versus sizes of agglomerated Pd-particles are considered to be studied in future.
- New metallo-ceramic catalytic elements with Pd are in the process of manufacturing. In metallo-ceramic catalytic elements, the nickel-aluminide diffusion layer formed between metallo-ceramic coating and nickel-base substrate significantly improves the adhesion properties. The performance characteristics, thermal and mechanical stability of these catalytic elements will be studied in future.



Figure 2 Single Tube Test Facility

	Volume (%)
CH₄	7.4
CO₂	7.9
CO	59.8
H₂	24.0
N₂	0.9

Table 2 Syngas Composition

	Volume (%)
CH₄	93.59
C₂H₆	2.38
C₃H₈	0.57
N₂	1.94
CO₂	0.79

Table 3 Natural Gas Composition

Coating	Natural Gas	Syngas
PCI	295 C	315 C
SWPC(Pd)	310 C	260 C

Table 4 Light off Temperature Data

Task II.4 – Development of Catalytic Module

Full Scale Module Test Facility

The required design changes to the test facility at the Siemens Power Generation Industrial (PGI) facility in Lincoln, England for testing of catalytic modules have been identified. This facility is capable of the pressure, temperature and flow conditions needed for module testing. In addition it is capable of operation on both natural gas and syngas fuel. The geometrical changes necessary for module testing should be accomplished next quarter.

The first module test campaign will be focused on facility verification with the baseline module design using the flared tube concept. This design will be tested on both natural gas and syngas. The baseline catalytic module is shown in Figure 3.

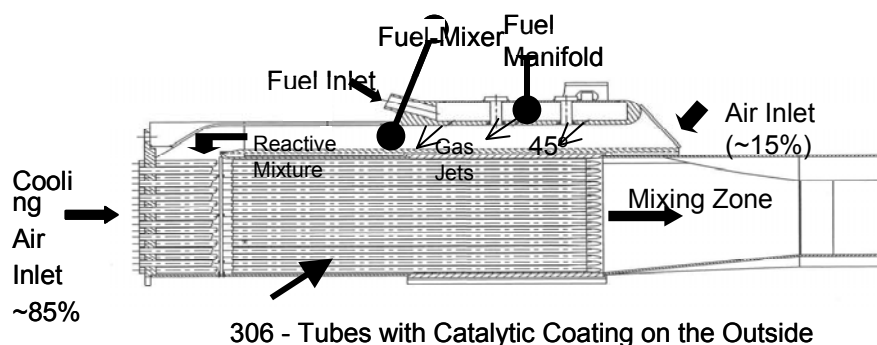


Figure 3 Base Catalytic Module Design

The baseline module is optimised for natural gas operation. A portion of the air (~15%) mixes with the fuel and reacts in fuel rich on the outside of the catalytically coated tubes. The remaining air flows inside of the tubes and acts to cool the catalyst. Both streams mix at the exit of the tubes and the mixture burns downstream. This design when tested in the lab at 501D5 conditions produced NO_x emissions of less than 1 ppm with acceptable CO burnout.

The goal of these tests is to maintain the basic design of the previous tests with modification necessary for syngas operation. The fuel injection pattern was designed for optimal performance at STG6-5000F conditions for both fuels. Because of the significant differences in volumetric fuel flow between natural gas and syngas, it is not possible to use the same fuel injectors for both fuels. The new design has been modified to incorporate a dual fuel manifold which is capable of operation on both fuels. The dual fuel design is shown below in Figure 4. The natural gas manifold is shortened and moved upstream to make room for the larger syngas manifold.

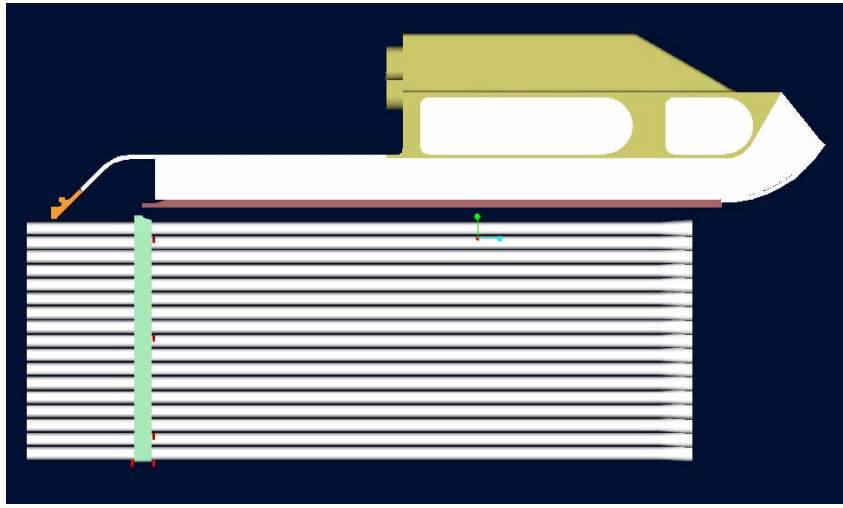


Figure 4 Dual Fuel Catalytic Module for Natural Gas and Syngas

In addition to the syngas manifold some changes were made to improve the manufacturability and mechanical integrity of the design. The mechanical integrity was improved by thickening the baffle plate and replacing the fillet welds on the outside of the module with full penetration welds. The manufacturability of the module was improved by shortening the scalloped section at the tube exit.

CFD analysis was used to evaluate the level of mixing in the fuel manifold. The goal was to match the level of unmixedness of the original design and insure that there are no potential flame holding regions in the manifold. Unmixedness is defined as:

$$U = \frac{\sqrt{\sum (Y_{fuel,i} - \bar{Y}_{fuel})^2 \Delta \dot{m}_i / \dot{m}_{total}}}{\bar{Y}_{fuel}}$$

where

$$\bar{Y}_{fuel} = \sum Y_{fuel} \Delta \dot{m}_i / \dot{m}_{total}$$

CFD results for the natural gas manifold are given in Figure 5. The unmixedness for this design was calculated to be 11.98%. The results for the syngas calculation are given in Figure 6. Unmixedness for this design was calculated as 10.77%.

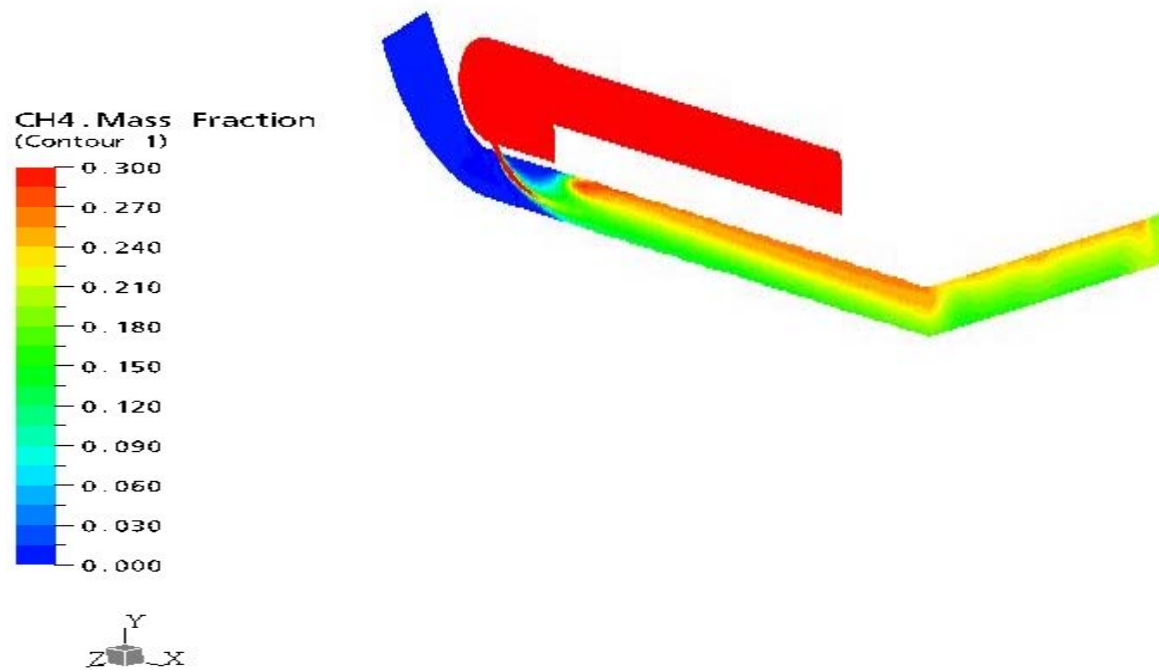


Figure 5 CFD Results for Mixing in the Natural Gas Manifold

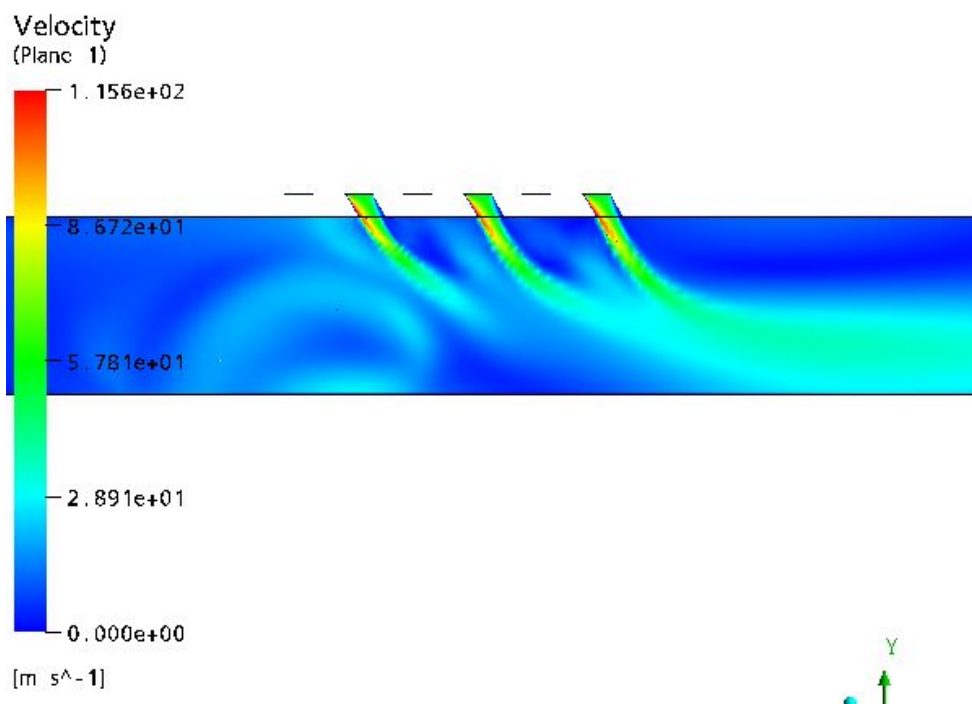


Figure 6 CFD Results for Mixing in the Syngas Manifold

This design was optimized for a 15% split flow on natural gas. Because of the larger fuel flow rates during syngas operation the split will be reduced to roughly 5% during syngas operation. This split can be increased by injecting nitrogen into the air in the cooling flows.

Task II.5 – Catalytic Combustor Basket

ENEL Basket Facility

Siemens uses the ENEL test facility in Italy and the DLR test facility in Cologne, Germany for full scale combustor basket testing. Both of these facilities can produce the required pressure, temperature and flows to simulate 501FD conditions in a single basket. Both facilities have the capabilities to provide both natural gas and syngas fuel at base load 501FD conditions. Either facility can be used for testing depending upon rig availability. Siemens has a rig which simulates the geometry of the engine casing for a single basket in the 501F frame. Figure 7 shows the 501FD test rig as installed at ENEL.

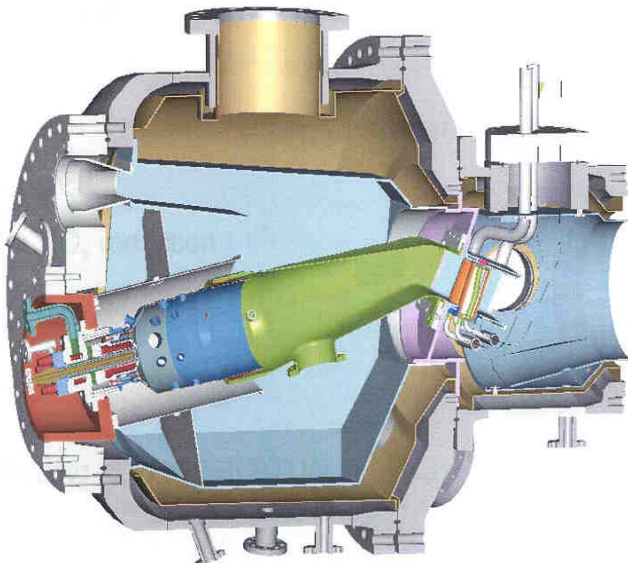
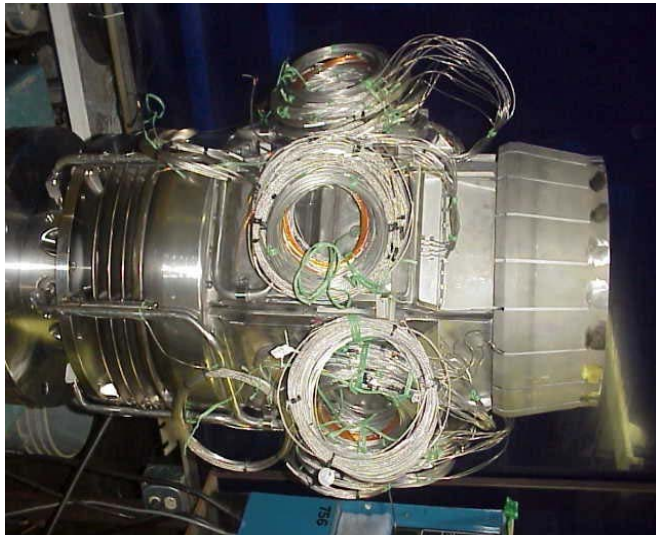


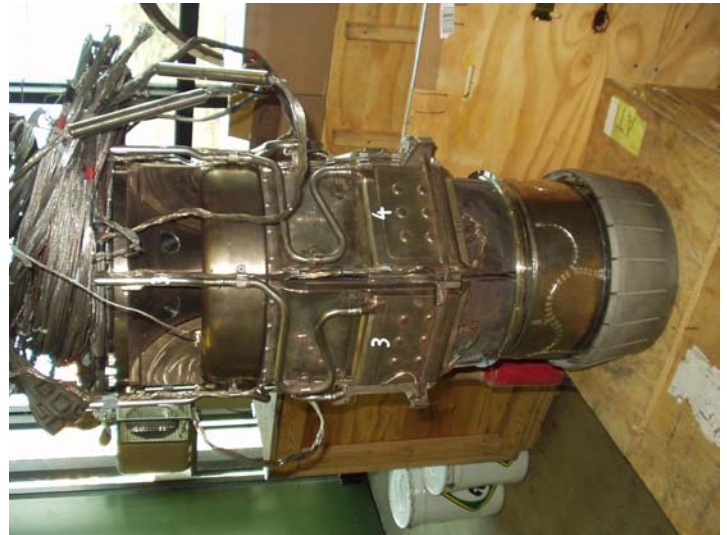
Figure 7 – Combustor basket test facility

Siemens has performed full basket testing on a catalytic basket designed for the 501D5 engine. This design produced NO_x emissions in the range of 2 – 3 ppm NO_x at 501D5 conditions. The main limitations of the design were CO burnout due to the short length of the basket and relatively low firing temperature of the 501D5 engine. Some data was obtained in the D5 geometry with the conditions typical of the STG6-5000F engine. With the higher firing temperature and compressor exit temperature typical of the STG6-5000F engine NO_x was measured at 3.6 ppm and CO was measured at 9 ppm.

For this program the 501D5 basket was modified to fit into the casing of the STG6-5000F engine. This modification involved relocating the fuel inlet pipes, modifying the head end of the basket and adding a longer liner. The longer liner should improve the CO burnout issues encountered during the testing on the 501D5 engine. Figure 8 shows the original 501D5 basket and the basket after modification to the STG-5000F geometry. Figures 9 and 10 show the basket as installed in the D5 and F engine. The geometry of the STG6-5000F gives a much longer burnout section.



A) D5 Basket



B) F Basket

Figure 8 Catalytic Combustor Basket

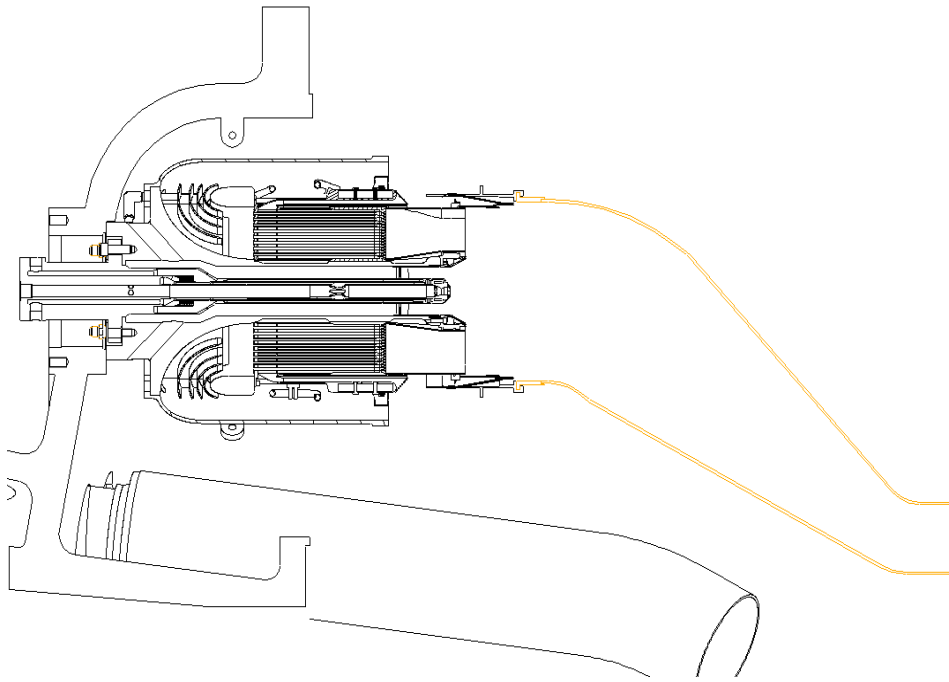


Figure 9 Catalytic Combustor in the 501D5

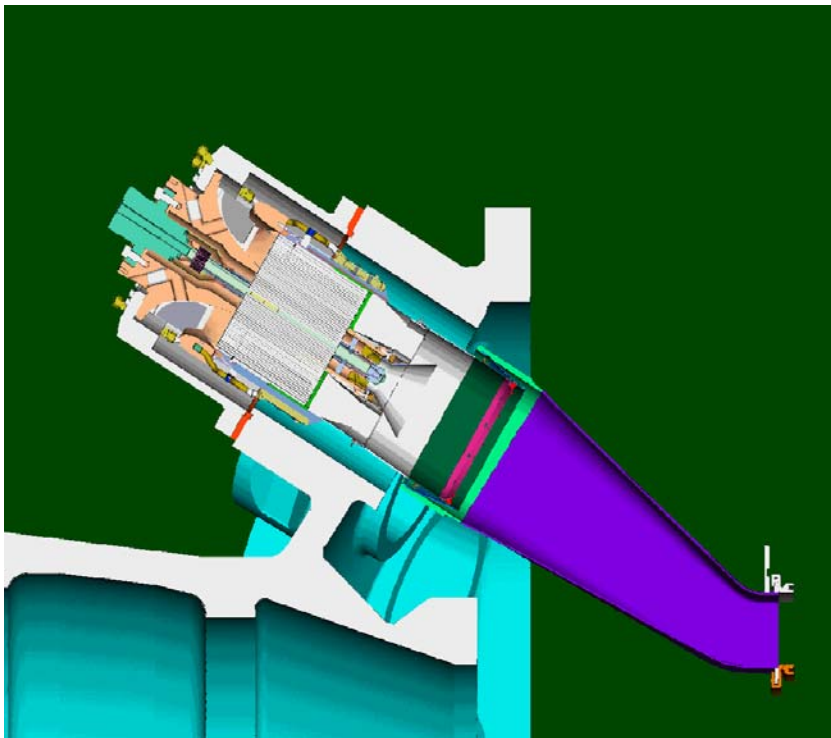


Figure 10 Catalytic Combustor in the STG6-5000F

Testing was performed on the STG6-5000F basket at the ENEL test facility in Italy. The purpose of the testing was to verify that the combustor dynamics, emissions and basket metal temperatures were within limits. Figure 11 shows typical combustion dynamics during the test. The main frequency of the combustor dynamics was 100 Hz and the amplitude was in the range 0.25-0.5 psi. These dynamics are similar to those recorded in the 501D5 testing and are well below the design limits of 2.0 psi. Basket, catalyst and transition metal temperatures were all well below the limits of 900 C.

Figure 12 compares the data obtained in the STG6-5000F rig with that obtained at F conditions in the previous testing in the 501D5 configuration. The NO_x emissions for the current tests were roughly double those obtained in the previous test campaign. With the diffusion pilot shut off completely the NO_x emissions on the current program were 8 ppm as compared to 3.6 ppm in the previous tests. In the previous testing decreasing the pilot decreased the NO_x and increased CO emissions as would be expected. In these tests decreasing the pilot decreased both the NO_x and the CO.

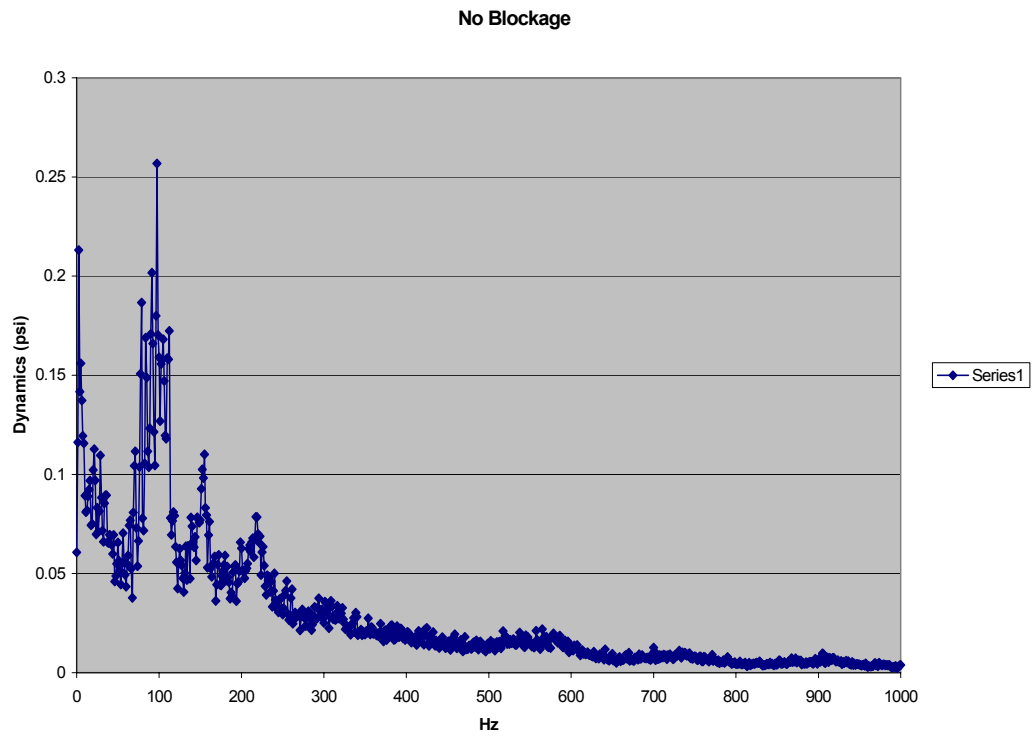


Figure 11 Combustion Dynamics

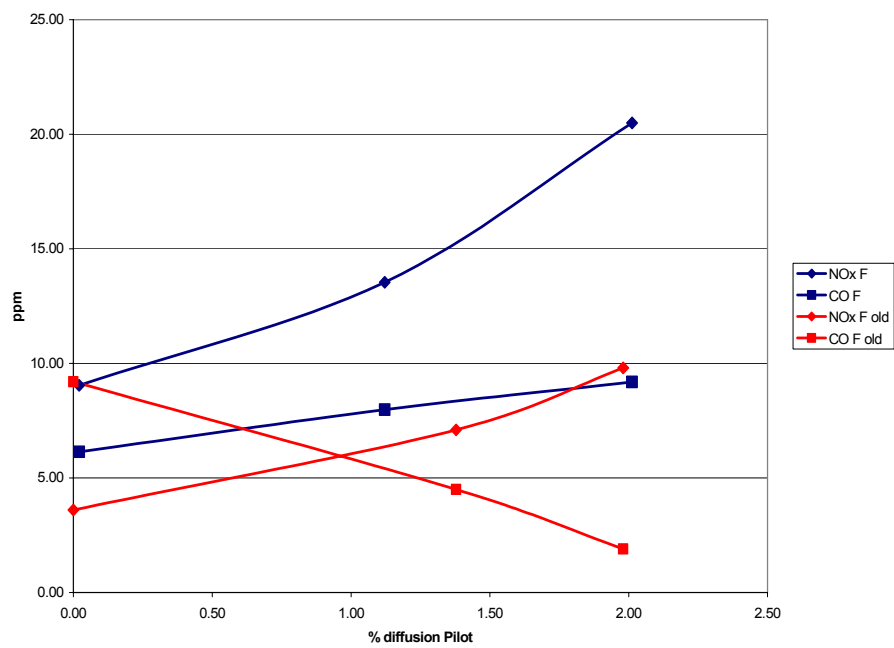


Figure 12 Emissions Data Comparison

A comparison of the data between the two test configurations at the same conditions is shown in Table 5. For the same conditions the catalyst surface temperature and the catalyst exit temperature are increased. This could be caused by an increase in the air split to the rich side of the catalyst, or by an decrease in the total amount of air to the modules. The air splits measured by the gas chromatograph were consistently 11 to 12 % for both test configurations. The other possibility is air leakage bypassing the modules, causing them to run at a lower AFR.

	D5 Configuration	F Configuration
Diffusion Pilot	2%	2%
Premixed Pilot	6%	6%
NOx	9.8 ppm	20.5 ppm
CO	1.9 ppm	9.2 ppm
Catalyst Surface Temp	706 C	753 C
Catalyst Exit Gas Temp	563 C	620 C

Table 5 Comparison of Data Between D5 and F Configuration

Examination of the modules at the conclusion of the test revealed that the gaps between the module exits and the sealing surface were not maintained to the original drawing tolerances. The rope seals which were designed to eliminate leakage air between the modules were no longer in place at several locations. Figure 13 shows the region between the modules. Nichrome strips were placed over these locations in an attempt to eliminate the leakage but they did not make a substantial difference in the results. Even with the nichrome in place there was substantial leakage around the modules.



Figure 13 Potential Air Leakage Path Between Modules

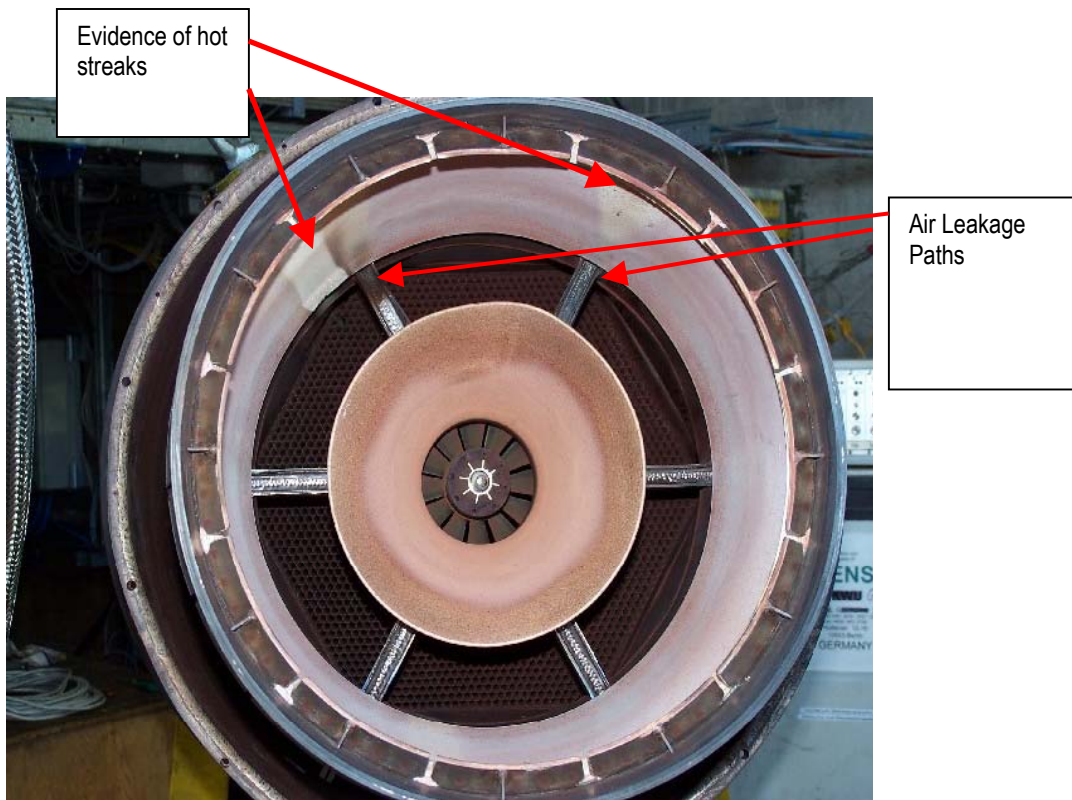
Figure 14 contains a photograph of the basket at the conclusion of the testing. Evidence of overheating can be seen on the liner in two locations. There is also evidence of flame holding near the module exits at these locations.

The basket liner clearly shows evidence of hot spots in the flame zone. These non uniformities would explain the high NO_x emissions. The main source of these hot streaks would leakage air around the modules.

The next steps in the program are:

- Perform effective area measurements on the basket to determine the source of the leakage.
- Perform CFD analysis on the basket in the STG6-5000F geometry to determine the effects of the basket length and transition shape on the burnout region.
- Rebuild the basket with the proper gaps around the module.
- Retest the basket on natural gas.

Figure 14 Basket After Test



STATUS OF MILESTONES

First Quarter

10/1/04-12/31/04

Obtain Light off data on SWPC coating on both natural gas and syngas.

Status: complete

Second Quarter

1/1/05-3/31/05

Modify basket design to 501F configuration required for syngas and test.

Status: complete

Third quarter

4/1/05- 6/30/05

Flashback testing in the 60 tube rig

Status: on target

Forth Quarter

7/1/05-9/30/05

Subscale testing on hydrogen

Status: on target

CONCLUSIONS

The major accomplishments during this phase of the project are:

- An SWPC coating has been identified which meets the light off targets on both natural gas and syngas.
- The catalytic module has been redesign to include a dual fuel manifold for syngas. Additional changes were incorporated for improved mechanical integrity and manufacturability.
- The catalytic basket was redesigned for the STG6-5000F geometry. This redesigned basket was tested at the Siemens high pressure test facility at ENEL in Italy.
- The single tube facility was moved from Pittsburgh to Casselberry, Florida and in now operational.

- The 60 tube test facility was moved from Pittsburgh to Casselberry, Florida and is now operational.

The expected activity during the next six months includes:

- Continue coating screening in the single tube rig
- Begin coating durability studies
- Perform flashback testing on capture plates
- Perform subscale testing on hydrogen fuel
- Perform catalytic module tests on the baseline design for both natural gas and syngas